HIGH VOLTAGE PULSE GENERATION IN 10-MEGAMPERE PLASMA FLOW SWITCH EXPERIMENTS

M.L. Alme, G. Bird, C. Boyer, S.K. Coffey, D. Conte,
J.F. Davis, S.W. Seiler, P.J. Turchi
R&D Associates, Inc.
301 S. West St., Alexandria, VA 22314

W.L. Baker, J.H. Degnan, D.J. Hall, J.L. Holmes,
J.B. Kriebel, W.F. McCullough, D.W. Price
Air Force Weapons Laboratory
Kirtland AFB, NM 87117-6008

J. Buff, M.H. Frese, R.E. Peterkin, Jr., N.F. Roderick
Mission Research Corporation
1720 Randolph Rd, SE
Albuquerque, NM 87106

J.D. Graham, E.A. Lopez
Maxwell Laboratories, Inc.
P.O. Box 9350
Albuquerque, NM 87119

Abstract

The Plasma Flow Switch utilizes the dynamics of a plasma discharge in vacuum to accumulate magnetic energy in several microseconds and then release this energy to a load region in a few hundred nanoseconds. Experiments have previously been performed using the plasma flow switch on the Shiva Star capacitor bank to drive imploding plasma loads at multimegajoule, multi-megampere levels. Recently, experiments have been conducted in which a portion of the switch plasma is used as the current carrying load. These experiments employed the Shiva Star capacitor bank, charged initially to 84 kV (4.6 MJ) to achieve currents in excess of 10 megamperes at the switch region. Comparisons of voltage measurements in the bank transmission line with numerical simulations (MACH2 computer code) indicate that the low density, very high speed flow in the switch supports voltages in excess of 0.5 megavolts at the coaxial gun muzzle. Measurements of hard X-radiation (> 10-100 keV) imply the existence of high energy electrons and are consistent with the generation of high voltages in the plasma flow switch.

Introduction

Over the last several years, experiments have been performed on the Shiva Star capacitor bank at the Air Force Weapons Laboratory in which a particular coaxial plasma gun configuration called the Plasma Flow Switch has been used for inductive storage and switching [1,2]. The plasma flow switch (Figure 1) comprises two coaxial electrodes connected in series with a high current source by a high density, annular plasma discharge; it is arranged that vacuum exists initially both upstream and downstream of the annular discharge. The principal application of this arrangement has been to drive plasma liner implosions to achieve high energy, high temperature, radiating plasmas. Earlier efforts [3,4], begun in 1971 at AFWL, indicated the need for submicrosecond, multi-megajoule delivery of electromagnetic energy to drive useful plasma liner implosions. Experiments at AFWL have included both direct-drive from fast capacitor banks and inductive- drive [5] using exploding-foil fuses to sharpen the pulse from a capacitor bank. The more recent approach using a plasma flow switch has provided in excess of 0.5 MJ of soft X-radiation with an initial capacitor bank energy of only 4 MJ [6]. The purpose of the present series of experiments (termed 'Open Fire' in comparison to the earlier 'Quick Fire' series) has been to investigate the voltage level that could be supported by the plasma flow switch during and after the diversion of current to the load region.

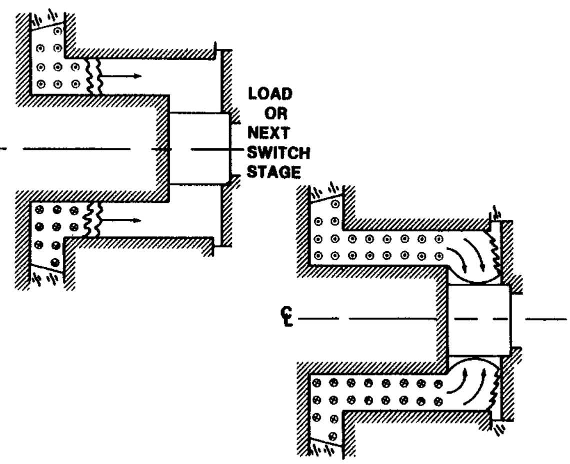

Fig 1: Schematic of Plasma Flow Switch operation. a) Magnetic energy accumulates in coaxial inductive store as annular discharge (drive-plasma) is accelerated axially downstream by jxB forces. b) Magnetic energy can flow to load (shown as cylindrical liner implosion) as high mass density drive-plasma passes off the end of the center conductor.

The Plasma Flow Switch

In the Quick Fire series of experiments [6,7], the original helical vacuum power feed and baffle structure [1,8] successfully employed in the Mark IV and Mark VI plasma flow switch experiments at AFWL, was replaced with a pair of nested stepped cone transmission plates fabricated by metal-spinning techniques. The vacuum-plastic insulator interface design [8] was essentially unchanged. Typical operation of the plasma flow switch involved initial bank energies of 4-6 MJ, initial bank voltages of 80-100 kV, peak currents of 10-15 MA and risetimes of 3-4 μsec. The main annulus of switch plasma achieved a speed of about 70 km/sec as it swept off the end of the center conductor (cathode), with most of the current diverted

Report Documentation Page					*Form Approved OMB No. 0704-0188*
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE **JUN 1987**		2. REPORT TYPE **N/A**			3. DATES COVERED **-**
4. TITLE AND SUBTITLE **High Voltage Pulse Generation In 10-Megampere Plasma Flow Switch Experiments**					5a. CONTRACT NUMBER
					5b. GRANT NUMBER
					5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)					5d. PROJECT NUMBER
					5e. TASK NUMBER
					5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **R&D Associates, Inc. 301 S. West St., Alexandria, VA 22314**					8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)					10. SPONSOR/MONITOR'S ACRONYM(S)
					11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**					
13. SUPPLEMENTARY NOTES **See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.**					
14. ABSTRACT **The Plasma Flow Switch utilizes the dynamics of a plasma discharge in vacuum to accumulate magnetic energy in several microseconds and then release this energy to a load region in a few hundred nanoseconds. Experiments have previously been performed using the plasma flow switch on the Shiva Star capacitor bank to drive imploding plasma loads at multimegajoule, multimegampere levels. Recently, experiments have been conducted in which a portion of the switch plasma is used as the current carrying load. These experiments employed the Shiva Star capacitor bank, charged initially to 84 kV (4.6 MJ) to achieve currents in excess of 10 megamperes at the switch region. Comparisons of voltage measurements in the bank transmission line with numerical simulations (MACH2 computer code) indicate that the low density, very high speed flow in the switch supports voltages in excess of 0.5 megavolts at the coaxial gun muzzle. Measurements of hard X-radiation (> 10-100 keV) imply the existence of high energy electrons and are consistent with the generation of high voltages in the plasma flow switch.**					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

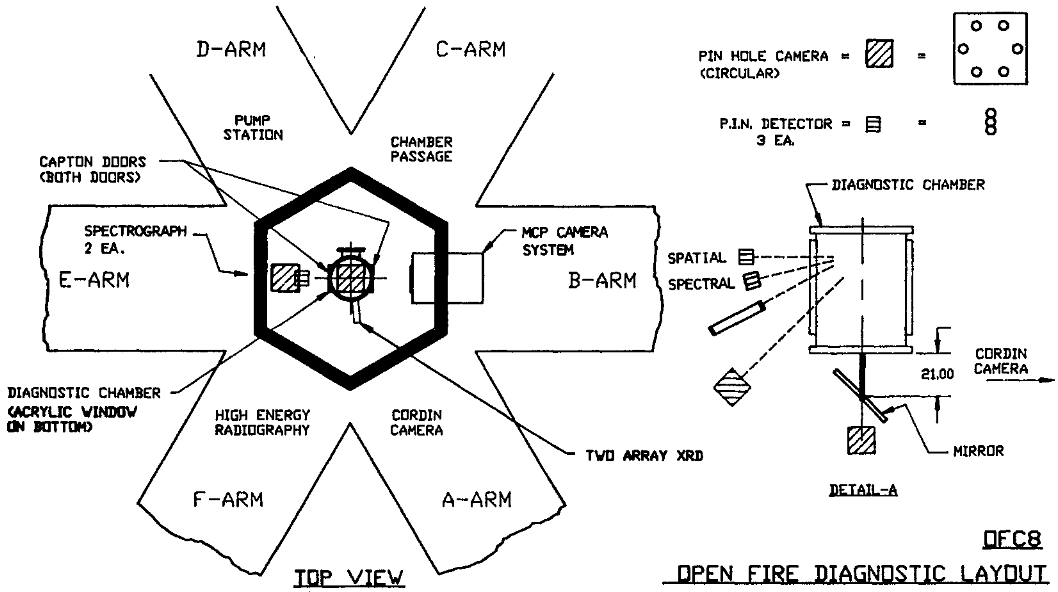

Fig 2: Overall schematic of Open Fire Experiment indicating radiation views.

to the load region in about 200-300 nsec. (Plasma implosions in times of 500 nsec or less were thus capable of obtaining at least half of the total current delivered to the coaxial gun, while slow-moving, thick-walled cylindrical liners received almost all of the current.) Comparisons of calculations for plasma flow switch-driven implosions (including zero-dimensional slug models and two-dimensional MHD codes [9]), with experimental data indicate that a few hundred kilovolts should be sustained near the end of the center conductor across the low density, very high speed plasma flow (from which the Plasma Flow Switch derives its name).

'Open Fire' Experiments

To allow more rapid investigation of the processes by which the voltage is generated and supported in the plasma flow switch, the complex structure at the end of the gun required for plasma liner implosions was removed. The resulting open-ended system (hence 'Open Fire' vs 'Quick Fire') permitted improved diagnostic access and faster installation of experiments at multi-megajoule levels. The principal measurement techniques for the initial Open Fire experiments included terminal voltage and current monitors (just outside the vacuum-plastic interface of the Quick Fire feed), magnetic field probes (pickup coils) in the feed and coaxial gun, optical fast-framing/streak photography, and hard X-ray detectors outside the vacuum tank (both X-ray pinhole cameras and PIN detectors). The basic experimental arrangement for Open Fire is shown in Figure 2.

Initial conditions for system operation were held fixed as diagnostics and downstream structures were changed. The initial bank voltage for all tests was nominally 84 kV for which the stored energy of Shiva Star is 4.6 MJ. This initial voltage provided a peak current of about 11 MA as the main discharge plasma reached the exit of the coaxial gun. The plasma was formed by electrical explosion of a plurality of fine wires that crossed the interelectrode gap in a chordal pattern. Tests were conducted using both aluminum and tungsten wire arrays with a total mass in the interelectrode gap of 100 mg. Typical voltage and current traces are displayed in Figure 3. The voltage shown is measured by a capacitive voltage divider in the flat-plate transmission section just outside of the Quick Fire vacuum feed. The current signal is from magnetic probes in the vacuum feed well upstream of the initial plasma position. (It agrees in shape with the Rogowski coils outside the vacuum-plastic insulator, but has better frequency response and a more accurate calibration factor.) For comparison, the predicted behavior of voltage and current from calculations using the MACH2 code [9] are displayed in Figure 4. Note that the timing and amplitude of both the voltage and current traces are in excellent agreement with experimental data. Such agreement lends credence to code predictions of the plasma flow dynamics, and tends to be confirmed by the amplitudes and arrival times of magnetic field levels monitored by probes in the discharge flow. Good agreement between experiment and theory provides the basis for reasonable estimates of particle densities and velocities in the plasma flow switch. (Such estimates would be very difficult to achieve by experimental techniques alone, particularly over the entire flow field.) In this way, the terminal voltage and current monitors serve together as a kind of plasma flow meter sensing the uxB electric field across the flow and thereby measuring the plasma speed.

It is typical in pulsed power experiments to correct the terminal voltage for inductive contributions between the voltage probe and a lumped-element load. For a load involving a distributed dynamic plasma discharge, such correction requires an MHD calculation, which MACH2 provides. In the Open Fire series, the peak voltage at the capacitive divider of 130-160 kV corresponds to a peak voltage across the muzzle of the coaxial gun in excess of 500 kV. For currents at the time of the voltage peak of about 10 MA, the magnetic field in the coaxial gun varies across the gap from 20-27 T, so spatially-averaged plasma speeds of 800 km/sec could be estimated from the corrected peak voltage level. The MACH2 calculations, of course, provide plasma speeds corresponding to the total voltage calculation directly for all positions within the gun and downstream exit flow. Speeds of 1000-2000 km/sec are computed in some regions. For such speeds, the kinetic energy of aluminum and tungsten ions are, respectively, 140-560 keV and 0.9-3.7 MeV. Ion densities in these very high speed flows are much lower than in the main switch plasma, 10^{15} - 10^{16} cm^{-3} vs 10^{18} - 10^{19} cm^{-3}, but would imply equivalent (charge- and current-neutralized) ion beam currents of 10-100 MA.

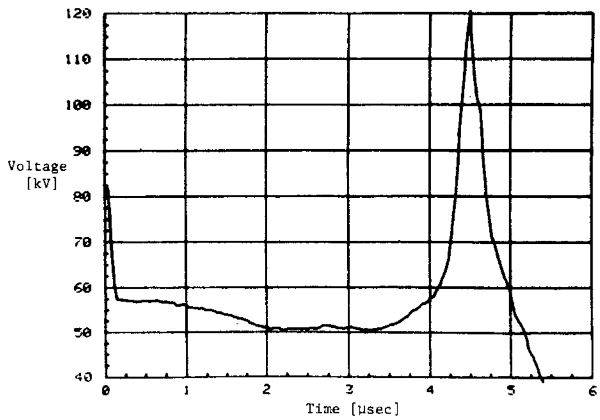

Fig 3a: Capacitive voltage divider signal vs time.

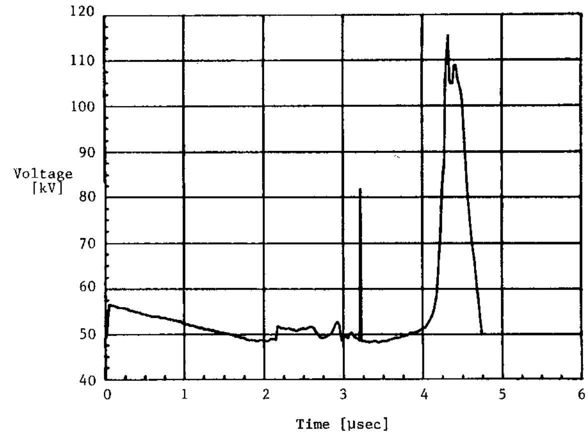

Fig 4a: Predicted voltage divider signal from MACH2 computer code. (Note suppressed zero.)

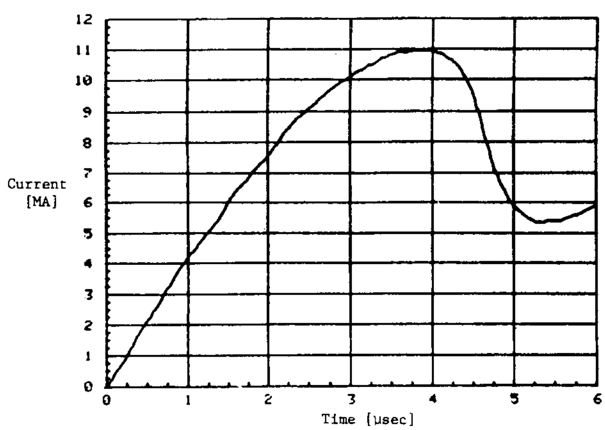

Fig 3b: Total current vs time.

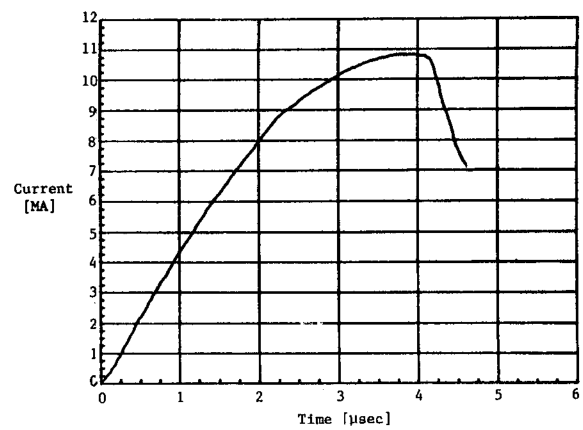

Fig 4b: Predicted total current signal from MACH2 computer code.

Radiation Measurements

It might be expected that a plasma discharge involving tens of megampere equivalent-currents of several hundred kilovolt to megavolt kinetic energy particles would produce noticeable amounts of hard X-radiation. Indeed, the few hundreds of kilovolts sustained across the coaxial gun is sufficient reason to monitor the experiment for evidence of X-rays. Such X-radiation would provide additional information about plasma flow switch dynamics. In particular, it is useful to correlate the predicted voltage in the load region with the X-radiation spectrum and timing in order to confirm the correction procedure for the capacitive voltage divider signal. Such correlation is necessary in other complex load situations, such as intense beam diodes, in which the load inductance is not precisely known (except by modeling). Correction of external voltage signals to obtain the voltage at the load is corroborated in these cases by inferring the electron beam energies from the (bremsstrahlung) X-radiation spectrum.

For the plasma flow switch, interpretation of the X-ray pulse in terms of beam-target bremsstrahlung from an electron beam accelerated by the gun voltage is complicated by difficulties with simple models for beam dynamics. In particular, at the relative high magnetic fields present in the plasma flow, gyroradii are too small for electric field acceleration of electrons to high energies. Since the entire region of plasma flow switch action is filled with plasma at a temperature of a few electron volts, local electric fields are largely a manifestation of the back electromotive force, $E \approx -uxB$ [10]. If the electrons are collisionless, the electron velocity will be the drift speed E/B, which is equal to the local plasma flow speed. Electric fields in the plasma flow switch thus can accelerate electrons only up to the local ion speed. For u = 2000 km/sec, the electron kinetic energy would be less than 12 eV. Near the center line, or other regions of zero magnetic field, the electron gyroradius may exceed the distance of the electron from the zero field point so that excursions of electrons for greater distances along the local electric field might be possible. Electron trajectories in pinch filaments have been considered in devices such as the dense plasma focus and can allow high energy electron beams. Evidence for such beams would be fine filamentary sources of X-radiation, which are indeed observed in plasma focus and related pinch discharges. Time-integrated X-ray pinhole photography of the plasma flow switch (muzzle and downstream flow) instead display a diffuse X-ray source.

Filtered pinhole cameras viewed the discharge region both through a Plexiglas window (0.5-0.75 inch thick) and through the stainless vacuum vessel wall (0.25 inch thick), corresponding to low energy cutoffs of about 20 keV and 80 keV, respectively. Both sets of photographic views in tests with both aluminum and tungsten wire arrays (of the same total mass) indicated toroidal regions of X-ray emission on the cathode end-face and in the downstream flow (with some large scale azimuthal variations in the downstream regions). Typical source dimensions from the time-integrated images were 5-15 centimeters (diameter, axial length, and azimuthal variations). It is certainly possible that fine-scale beam structures or pinch-like structures exist in the flow, and are obscured by motion or by the presence of diffuse radiating plasma. The present photos nevertheless

differ qualitatively from time-integrated X-ray photos of dense plasma focus discharges (that show only tight filaments).

Filtered PIN detectors have been used to obtain temporal and spectral information (with only limited spatial resolution). A representative trace is shown in Figure 5, along with the corresponding terminal voltage signal. In all of the Open Fire experiments to date, the X-ray pulse occurs 100-200 nsec after the peak of the voltage pulse. This time-lag precludes simple beam-target models as used for electron beam diodes and requires instead some mechanism(s) for storing energy delivered through the plasma flow switch. There are several candidate models to be evaluated. For example, high speed ions associated with the voltage across the gun muzzle could be trapped by the magnetic field in plasma flow stagnating downstream. These ions then would be slowed by electron drag [11], heating the electrons to temperature levels of a few tens of keV for which free-free and free-bound inelastic events would produce hard X-radiation. The presence of X-rays correlates with the voltage pulse across a high speed plasma flow, but there would be a time lag due to ion transit over the 10-20 cm dimensions of the cathode diameter and downstream stagnation region. Magnetic energy storage followed by resistive tearing-mode instability [12] in the downstream plasma is also an interesting possibility.

Concluding Remarks

The purpose of the Open Fire experiments has been to examine the voltage capabilities of the plasma flow switch. Previous experiments (e.g., Quick Fire series) involved plasma liner implosions for which the voltage experienced by the switch region was limited to that demanded by the implosion load. The present tests demonstrate that the plasma flow switch can support at least a half a megavolt at current levels of ten megamperes. The voltage pulse rises sharply, with a pulsewidth of 100-200 nsec. Excellent agreement between experimental data and the magnetohydrodynamic model embodied in the MACH2 computer code indicates that the voltage results from the back EMF across a very high speed, low density plasma flow that follows the main switch plasma. Such a plasma flow would sustain a high electric field (-uxB) in the switch region as long as the magnetic field (i.e., the total current) is maintained. In fact, if the drive current persists long enough, it should be expected that the low density plasma flow would achieve a steady pattern resembling the current and velocity distribution in magnetoplasmadynamic arcjets [13].

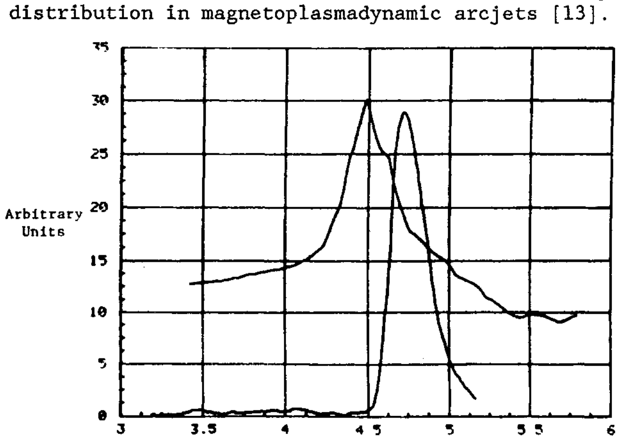

Fig 5: Overlay of capacitive voltage divider and PIN X-ray detector signals (later one is PIN signal).

Earlier modeling [2] of the plasma flow in terms of a frozen magnetic field assumption appears to be validated by the MACH2 calculations. A consequence of the frozen field situation is a limitation on the release of electromagnetic energy from the low density plasma flow, except in regions of radially converging flow (e.g., pinch filaments) or portions of the flow where effective collisionality is enhanced (e.g., electrode sheaths and regions of microinstabilities). For driving plasma liner implosions, energy is extracted by means of the work performed on the liner by the magnetized plasma flow. In the case of Open Fire-type arrangements, electromagnetic energy can be diverted to a load upstream of the plasma flow switch, using the switch voltage to commutate current into an initially lower impedance path. It may be more interesting and useful, however, to employ the plasma flow switch itself as the load, recognizing that in the Open Fire series the switch performs in the manner of a magnetized plasma-filled ion diode. Such a diode (perhaps more properly termed a Hall accelerator [14]) avoids space-charge limitations and appears to be capable of megavolt ion energies at equivalent currents of tens of megamperes.

REFERENCES

[1] P.J. Turchi, et al, in Proceedings of the 3rd IEEE International Pulsed Power Conference, 1-3 June 1981, Albuquerque, NM. IEEE Cat. No. 81CH1662-6, pp. 455-462.

[2] P.J. Turchi, et al, in Proceedings of the 4th IEEE Pulsed Power Conference, 6-8 June 1983, Albuquerque, NM. IEEE Cat. No. 83CH1908-3, pp. 342-345.

[3] P.J. Turchi, W.L. Baker, J. Appl. Phys., vol. 44, p. 4936 (1973).

[4] W.L. Baker, et al, J. Appl. Phys., vol., 49, p. 4694 (1978).

[5] R.E. Reinovsky, et al, in Proceedings of the 4th IEEE Pulsed Power Conference, 6-8 June 1983, Albuquerque, NM. IEEE Cat. No. 83CH1908-3, pp. 196-201.

[6] W.L. Baker, et al, in Proceedings of the 6th IEEE Pulsed Power Conference, 29 June-1 July 1987, Arlington, VA. Paper No. 16-5.

[7] W.L. Baker, et al, in Megagauss Technology and Pulsed Power Applications, eds. C.M. Fowler, R.S. Caird, D.J. Erickson. Plenum Press, NY, 1987, pp. 653-662.

[8] D. Conte, et al, in Proceedings of 9th Symposium on Engineering Problems of Fusion Research, 26-29 October 1981, Chicago, IL. IEEE Cat. No. 81CH1715-2 NPS, pp. 1502-1505.

[9] R.E. Peterkin, et al, in Megagauss Technology and Pulsed Power Applications, eds. C.M. Fowler, R.S. Caird, D.J. Erickson. Plenum Press, NY, 1987.

[10] P.J. Turchi, in Opening Switches, eds. A.H. Guenther, T.H. Martin, M. Kristiansen. Plenum Press, NY, 1987. Chapter Seven, "Plasmadynamic Opening Switch Techniques," pp. 191-208.

[11] L. Spitzer, Physics of Fully Ionized Gases. 2nd Edition. J. Wiley, NY, 1962, pp. 134-135.

[12] G. Schmidt, Physics of High Temperature Plasmas. 2nd Edition. Academic Press, NY, 1979, p. 147.

[13] R.G. Jahn, et al, AIAA J., Vol. 9, p. 167 (1971).

[14] R.G. Jahn, Physics of Electric Propulsion. McGraw-Hill, NY, 1968, p. 225.